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(54) Method and apparatus for tracking an object, in particular a catheter, using energy fields

(57) A method for tracking an object, including producing an unperturbed energy field at a plurality of predetermined frequencies in the vicinity of the object and determining a characteristic of a perturbing energy field induced responsive to the unperturbed field, due to introduction of an article, responsive to the unperturbed field, into the vicinity of the object. The method further includes receiving a plurality of resultant signals respon-

sive to the unperturbed and perturbing energy fields generated at a location of the object after introduction of the article, determining an optimal frequency for the unperturbed energy field from amongst the plurality of predetermined frequencies responsive to a parameter of the resultant signals, and determining spatial coordinates of the object responsive to the resultant signal at the optimal frequency.

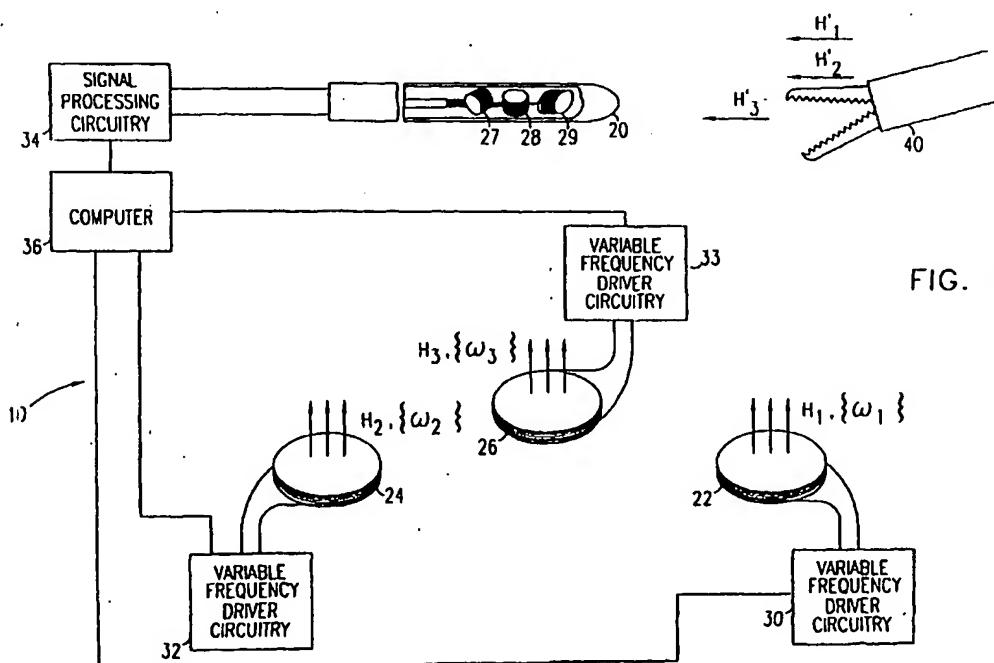


FIG. 2

EP 1 203 560 A2

Description**CROSS-REFERENCE TO RELATED APPLICATIONS**

5 [0001] This application is related to EP-A-0 993 804, the disclosure of which is incorporated herein by reference.

FIELD OF THE INVENTION

10 [0002] The present invention relates generally to non-contact tracking of objects using a magnetic field, and specifically to counteracting the effect of an intruding field-responsive article in the field.

BACKGROUND OF THE INVENTION

15 [0003] Non-contact electromagnetic tracking systems are well known in the art, with a wide range of applications.

[0004] U.S. Patent No.5,391,199, whose disclosure is incorporated herein by reference, describes a system for generating three-dimensional location information regarding a medical probe or catheter. A sensor coil is placed in the catheter and generates signals in response to externally applied magnetic fields. The magnetic fields are generated by three radiator coils, fixed to an external reference frame in known, mutually spaced locations. The amplitudes of the signals generated in response to each of the radiator coil fields are detected and used to compute the location of the sensor coil. Each radiator coil is preferably driven by driver circuitry to generate a field at a known frequency, distinct from that of other radiator coils, so that the signals generated by the sensor coil may be separated by frequency into components corresponding to the different radiator coils.

20 [0005] PCT patent publication WO96/05768 whose disclosure is incorporated herein by reference, describes a system that generates six-dimensional position and orientation information regarding the tip of a catheter. This system uses a plurality of sensor coils adjacent to a locatable site in the catheter, for example near its distal end, and a plurality of radiator coils fixed in an external reference frame. These coils generate signals in response to magnetic fields generated by the radiator coils, which signals allow for the computation of six location and orientation coordinates. As in the case of the '539 patent application described above, the radiator coils preferably operate simultaneously at different frequencies, for example at 1000, 2000 and 3000 Hz, respectively.

25 [0006] The above tracking systems rely on separation of position-responsive signals into components, most typically frequency components, wherein each such component is assumed to correspond uniquely to a single radiator coil, in a known position, radiating a magnetic field having a regular, well-defined spatial distribution. In practice, however, when a metal or other magnetically-responsive article is brought into the vicinity of the catheter or other object being tracked, the magnetic fields generated in this vicinity by the radiator coils are distorted. For example, the radiator coil's magnetic field may generate eddy currents in such an article, and the eddy currents will then cause a parasitic magnetic field to be radiated. Such parasitic fields and other types of distortion can lead to errors in determining the position of the object being tracked.

30 [0007] U. S. Patent 5,767,669 to Hansen et al., whose disclosure is incorporated herein by reference, describes a method for subtracting eddy current distortions produced in a magnetic tracking system. The system utilizes pulsed magnetic fields from a plurality of generators, and the presence of eddy currents is detected by measuring rates of change of currents generated in sensor coils used for tracking. The eddy currents are compensated for by adjusting the duration of the magnetic pulses.

35 [0008] U. S. Patent 4,945,305 to Blood, whose disclosure is incorporated herein by reference, describes a tracking system which avoids the problems of eddy currents by using pulsed DC magnetic fields. Sensors which are able to detect DC fields are used in the system, and eddy currents are detected and adjusted for by utilizing the decay characteristics and the amplitudes of the eddy currents.

40 [0009] EP-A2-0 964 261, to Dumoulin, whose disclosure is incorporated herein by reference, describes systems for compensating for eddy currents in a tracking system using alternating magnetic field generators. In a first system the eddy currents are compensated for by first calibrating the system free from eddy currents, and then modifying the fields generated when the eddy currents are detected. In a second system the eddy currents are nullified by using one or more shielding coils placed near the generators.

45 [0010] Fig. 1 is a graph showing a relation of the permeability μ of a ferromagnetic material in a magnetic field vs. frequency f at which the field is being generated, as is known in the art. Permeability μ is a factor in the phase shift generated by the magnetic field. The graph applies to a change of the permeability μ of the ferromagnetic material, generated for an article wherein eddy currents are formed. The change reflects the phase shift in a sensor, caused by the article, vs. the frequency f . As is known in the art, additional factors affecting the phase shift are geometry of the article, and conductivity of the material. The graph shows a virtually linear change in permeability for small changes in frequency.

SUMMARY OF THE INVENTION

[0011] It is an object of some aspects of the present invention to provide methods and apparatus for non-contact tracking of an object in an energy field in the presence of an article which interferes with the field.

5 [0012] It is another object of some aspects of the present invention to provide methods and apparatus for minimizing the effect of an article which interferes with an energy field used for non-contact tracking of an object.

[0013] In a preferred embodiment of the present invention, an object tracking system comprises one or more sensor coils adjacent to a locatable point on an object being tracked, and one or more radiator coils, which generate alternating energy fields comprising magnetic fields, in a vicinity of the object when driven by respective alternating electrical currents. For each radiator coil, a frequency of its alternating electrical current is scanned through a plurality of values so that, at any specific time, each of the radiator coils radiates at a frequency which is different from the frequencies with which the other radiator coils are radiating.

10 [0014] The sensor coils generate electrical signals responsive to the magnetic fields, which signals are received by signal processing circuitry and analyzed by a computer or other processor. When a metal or other field-responsive article is in the vicinity of the object, the signals typically include position signal components responsive to the magnetic fields generated by the radiator coils at their respective instantaneous driving frequencies, and parasitic signal components responsive to parasitic magnetic fields generated due to the article. The parasitic components are typically equal in frequency to the instantaneous frequency of the driving frequency, but are shifted in phase, so that the effect at each sensor coil is to produce a combined signal having a phase and an amplitude which are shifted relative to the signal when no field-responsive article is present. The phase-shift is a function of the driving frequency, and so will vary as each driving frequency is scanned. The computer processes the combined signal to find which frequency produces a minimum phase-shift, and thus a minimum effect of the parasitic components, and this frequency is used to calculate the position of the object. Varying the driving frequency until the phase shift is a minimum is an effective method, not known in the art, for reducing the effect of field-responsive articles on the signal.

15 [0015] In preferred embodiments of the present invention, an alternative method is also used in order to find a value of the position signal, i.e., of the signal produced without interfering effects of the field-responsive article. Measurements of the value of the combined signal are made at a plurality of frequencies. The values obtained are used to solve a plurality of simultaneous equations comprising the position signal as one of the unknowns in the equations. Thus, varying the driving frequency enables the position signal to be determined in the presence of interfering signals from field-responsive articles.

20 [0016] The present invention relies on the fact that parasitic magnetic fields, generated by metal or other field-responsive articles that receive and re-radiate energy from a radiator coil magnetic field are typically at the same frequency as the radiator coil field, but are shifted in phase relative thereto. The phase shift and the amplitudes of the parasitic fields generally depend on properties of the article, including dielectric constant, magnetic permeability and geometrical shape. However, both the phase shift and the amplitude of the parasitic fields can be assumed to be linearly dependent on the value of the frequency generating the parasitic field.

25 [0017] There is therefore provided, according to a preferred embodiment of the present invention, a method for tracking an object including:

30 40 producing an unperturbed energy field at a plurality of predetermined frequencies in the vicinity of the object; determining a characteristic of a perturbing energy field induced responsive to the unperturbed field, due to introduction of an article responsive to the unperturbed field into the vicinity of the object; receiving a plurality of resultant signals responsive to the unperturbed and perturbing energy fields generated at a location of the object after introduction of the article;

45 determining an optimal frequency for the unperturbed energy field from amongst the plurality of predetermined frequencies responsive to a parameter of the resultant signals; and determining spatial coordinates of the object responsive to the resultant signal at the optimal frequency.

50 [0018] Preferably, producing the unperturbed energy field at the plurality of predetermined frequencies includes scanning the frequencies sequentially.

[0019] Further preferably, producing the unperturbed energy field at the plurality of predetermined frequencies includes multiplexing at least some of the frequencies.

[0020] Preferably, receiving the plurality of resultant signals includes:

55 55 measuring a baseline phase value ϕ_ω of each of the plurality of resultant signals at the respective plurality of predetermined frequencies before introduction of the article; and measuring a phase shift $\phi_\omega^{\text{total}}$ at the respective plurality of predetermined frequencies after introduction of the article, so that the parameter comprises a term $|\phi_\omega^{\text{total}} - \phi_\omega|$ for each of the plurality of predetermined frequencies; and

wherein determining the optimal frequency includes determining a frequency ω at which $| \phi_{\omega}^{\text{total}} - \phi_{\omega} |$ is a minimum.

[0021] Preferably, determining spatial coordinates of the object includes determining spatial coordinates responsive to an amplitude of a signal $| M_{\omega} |$ at the frequency ω .

5 [0022] Further preferably, determining spatial coordinates of the object includes determining spatial coordinates responsive to a phase of a signal M_{ω} at the frequency ω .

[0023] Preferably, producing the energy fields includes producing magnetic fields. Preferably, receiving the signals includes receiving electrical signals which are generated responsive to the magnetic fields.

[0024] There is further provided, according to a preferred embodiment of the present invention, a method for tracking an object, including:

10 producing an unperturbed energy field comprising a plurality of predetermined frequencies in the vicinity of the object;
 producing a perturbing energy field by introduction of an article responsive to the unperturbed field into the vicinity of the object;
 15 receiving a respective plurality of signals responsive to the unperturbed and perturbing energy fields generated at a location of the object after introduction of the article; and
 determining one or more factors conditional on spatial coordinates of the object responsive to the plurality of signals and the respective frequencies.

20 [0025] Preferably, determining the one or more factors includes:

assuming a phasor \bar{A}_{ω} of a signal responsive to the unperturbed energy field and a phasor \bar{A}'_{ω} of a signal responsive to the perturbing energy field to be directly proportional to a plurality of predetermined currents generating the fields; and

25 assuming a phase ϕ_{ω} of the signal responsive to the unperturbed energy field and a phase ϕ'_{ω} of the signal responsive to the perturbing energy field to be linearly dependent on the plurality of predetermined frequencies.

[0026] Preferably, the plurality of frequencies includes at least four frequencies, and the one or more factors include the spatial coordinates of the object.

30 [0027] Preferably, receiving the plurality of signals comprises receiving at least four values of a signal M_i at the at least four frequencies, and determining the one or more factors includes:

determining a value of a position signal amplitude A_0 , generated responsive to the unperturbed energy field, by substituting respective values of the signal M_i into an equation

$$35 \quad \bar{M}_i = \bar{A}_i + a_i' e^{i\phi_i'}$$

40 wherein \bar{M}_i is a phasor representing a measured field, \bar{A}_i is a phasor representing the unperturbed field, a_i' represents an amplitude of the perturbing field, ϕ_i' represents a phase of the perturbing field, and i represents at least four numbers respectively corresponding to the at least four frequencies, so as to generate at least four equations; and

solving the at least four equations for the position signal amplitude A_0 .

45 [0028] There is further provided, according to a preferred embodiment of the present invention, object tracking apparatus, comprising:

50 a radiator, which generates an energy field at a plurality of predetermined frequencies in the vicinity of the object; a sensor, fixed to the object, which generates a plurality of signals responsive to the energy field and to an interfering article responsive to the energy field; and

signal processing circuitry, which receives the plurality of signals from the sensor and determines an optimal frequency for the energy field from amongst the plurality of predetermined frequencies responsive to a parameter of the signals, and which determines position coordinates of the object responsive to the signal at the optimal frequency.

55 [0029] Preferably, the radiator generates the energy field at the plurality of predetermined frequencies by scanning the frequencies sequentially.

[0030] Further preferably, the radiator generates the energy field at the plurality of predetermined frequencies by

multiplexing at least some of the frequencies.

[0031] Preferably, the parameter includes a phase shift, and the optimal frequency includes the frequency where the phase shift is a minimum.

5 [0032] Preferably, the signal processing circuitry determines the position coordinates of the object responsive to an amplitude of one of the plurality of signals at the frequency where the phase shift is a minimum.

[0033] Preferably, the energy field includes a magnetic field.

[0034] Preferably, the plurality of signals include a plurality of electrical signals which are generated responsive to the magnetic field.

10 [0035] There is further provided, according to a preferred embodiment of the present invention, object tracking apparatus, including:

a radiator, which generates an energy field including a plurality of predetermined frequencies in the vicinity of the object;

15 a sensor, fixed to the object, which generates a respective plurality of signals responsive to the energy field and to an interfering article responsive to the energy field; and

signal processing circuitry, which receives the plurality of signals from the sensor and determines one or more factors conditional on spatial coordinates of the object responsive to the signals and their corresponding frequencies.

20 [0036] Preferably, the plurality of frequencies includes at least four frequencies, and wherein the one or more factors comprise the spatial coordinates of the object.

[0037] The present invention will be more fully understood from the following detailed description of the preferred embodiments thereof, taken together with the drawings, in which:

25 BRIEF DESCRIPTION OF THE DRAWINGS

[0038]

30 Fig. 1 is a graph showing a relation of the permeability μ of a ferromagnetic material in a magnetic field vs. frequency f at which the field is being generated, as is known in the art;

Fig. 2 schematically illustrates a system for tracking a probe, such as a catheter for medical use, according to a preferred embodiment of the present invention;

Fig. 3 is a vector diagram illustrating a relation between position and parasitic components of a signal generated in the system of Fig. 2, according to a preferred embodiment of the present invention; and

35 Fig. 4 is a schematic flow chart showing a method for choosing frequencies to track the probe of the system of Fig. 2, according to a preferred embodiment of the present invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

40 [0039] Reference is now made to Fig. 2, which schematically illustrates a system 10 for tracking a probe 20, such as a catheter for medical use, according to a preferred embodiment of the present invention. The operation of systems generally similar to system 10 are described in detail in the above-mentioned EP-A-0 993 804, U.S. Patent 5,391,199, and PCT patent publication WO/96/05768, which are incorporated herein by reference. System 10 comprises a plurality of radiator coils 22, 24 and 26. These coils generate respective magnetic fields \vec{H}_1 , \vec{H}_2 and \vec{H}_3 , at respective sets of frequencies $\{\omega_1\}$, $\{\omega_2\}$ and $\{\omega_3\}$, in the vicinity of probe 20. Each frequency set $\{\omega_1\}$, $\{\omega_2\}$ and $\{\omega_3\}$, comprises a plurality of individual frequencies. Most preferably, each of frequencies f_i in sets $\{\omega_1\}$, $\{\omega_2\}$ and $\{\omega_3\}$ is simply divisible by a common frequency f_0 , i.e., $f_i = k_1 f_0$ where k_1 is a whole number. In this case, a sampling period ΔT circuitry receiving radiated signals, which signals are explained in more detail hereinbelow, is preferably given by the following equation:

50

$$\Delta T = \frac{k_2}{f_0} \quad (1)$$

where k_2 represents a whole number.

55 [0040] Typical values of frequencies f_i in sets $\{\omega_1\}$, $\{\omega_2\}$ and $\{\omega_3\}$ comprise frequencies in the range 100 Hz - 20 kHz.

[0041] System 10 further comprises substantially similar variable frequency driver circuitry 30, 32 and 33, coupled to each of the radiator coils, which drive coils 22, 24 and 26 at the respective sets of frequencies $\{\omega_1\}$, $\{\omega_2\}$ and $\{\omega_3\}$. Most preferably, the sets of frequencies $\{\omega_1\}$, $\{\omega_2\}$ and $\{\omega_3\}$ at which the coils radiate are set by computer 36. Further

most preferably, at least some of the frequencies of each driver circuitry are multiplexed together, and after acquisition the resulting signals are analyzed in signal processing circuitry 34, as described in more detail below. Alternatively, the frequency of each driver circuitry is varied according to some other method known in the art, such as scanning the frequencies cyclically over time, and/or using one or more other methods of time multiplexing. Whichever method is used to vary the frequencies, at any instant in time a frequency radiated by a specific coil is set to be different from the frequency or frequencies radiated by all the other coils.

5 [0042] The probe includes sensor coils 27, 28 and 29, which generate electrical current signals in response to the magnetic fields. At any instant in time these signals comprise components of the specific frequencies $\{\omega_1\}$, $\{\omega_2\}$ and $\{\omega_3\}$ being generated, whose respective amplitudes are dependent on the position and orientation of probe 20. The signals generated by sensor coils 27, 28 and 29 are preferably received and processed by signal processing circuitry 34 and then used by computer 36 to calculate position and orientation coordinates of probe 20.

10 [0043] Fig. 2 shows three radiator coils 22, 24 and 26 and three sensor coils 27, 28 and 29 in a probe 20. It will be understood, however, that the present invention is equally applicable to tracking systems comprising one, two, four or more radiator coils and one, two or more sensor coils. For example, the present invention applies to a single axis system comprising one sensor coil, in which case the system most preferably comprises nine radiator coils.

15 [0044] In the absence of parasitic effects, the signals generated by sensor coils 27, 28 and 29 at any of frequencies $\{\omega_1\}$ are proportional to the amplitude of the time derivative of the projection of field \vec{H}_1 at probe 20 along the respective axes of the sensor coils. The signals generated at any of frequencies $\{\omega_2\}$ and $\{\omega_3\}$ are similarly proportional to the projections of \vec{H}_2 and \vec{H}_3 . Parasitic effects that may arise due to mutual inductance among the radiator coils are preferably substantially eliminated, as disclosed, for example, in PCT patent application no. PCT/IL/00100, whose disclosure is incorporated herein by reference.

20 [0045] Since the direction and amplitude of the magnetic field due to any one of radiator coils 22, 24 and 26 can be calculated easily using methods known in the art, the sensor coil signals due to the respective radiator coil field may be directly related to the sensor coil's distance from and orientation relative to the radiator coil. It will also be appreciated that in the absence of parasitic magnetic fields, such as will be described below, the phase of the signal at each specific frequency comprised in $\{\omega_1\}$, $\{\omega_2\}$ and $\{\omega_3\}$ is substantially constant relative to the phase of the magnetic field generated by radiator coils 22, 24, 26, and depends on the position and orientation of sensor coils 27, 28, 29.

25 [0046] As shown in Fig. 2, however, when a metal or magnetic field-responsive article, for example a surgical tool 40, is introduced into the vicinity of probe 20, the article will generally receive energy from unperturbed fields \vec{H}_1 , \vec{H}_2 and \vec{H}_3 , and re-radiate perturbing parasitic magnetic fields, \vec{H}'_1 , \vec{H}'_2 and \vec{H}'_3 , at the specific frequencies from sets $\{\omega_1\}$, $\{\omega_2\}$ and $\{\omega_3\}$ which are being generated. Generally the phases of the parasitic fields will be shifted relative to the radiator coil fields by phase angles ϕ_1' , ϕ_2' and ϕ_3' , respectively. The phases and amplitudes of the parasitic fields generally depend on properties of tool 40, including its dielectric constant, magnetic permeability, geometrical shape and orientation relative to the radiator coils. The phases and amplitudes of the parasitic fields are also a function of the specific frequencies being generated.

30 [0047] Fig. 3 is a vector diagram illustrating a relation between the position and parasitic signal components, for radiation from radiator coil 22 at sensor coil 27, according to a preferred embodiment of the present invention. Coil 27 generates a set of frequencies, responsive to the frequencies generated by radiator coils 22, 24 and 26, which are transferred to signal processing circuitry 34. Circuitry 34 separates the received signal into constituent frequencies, and recovers the amplitude and phase of each frequency, which are used as described hereinbelow with reference to Fig. 3. In the interests of simplicity, unless indicated otherwise the following explanation refers to sensor coil 27, although it will be appreciated that sensor coils 28, and 29 behave substantially as coil 27.

35 [0048] Signal vector 50, having an amplitude $|M_{\{\omega\}}|$ and a phase $\phi_{\{\omega\}}^{\text{total}}$, represents a signal $M_{\{\omega\}}$ received from sensor coil 27 at a set of frequencies $\{\omega\}$. Vector 50 is the vector sum of position signal component vector 52 and parasitic signal component vector 54. Vectors 50, 52, and 54 are referenced in phase to a current $I_{\{\omega\}}$ in coil 27. Position signal component 52 has amplitude $A_{\{\omega\}}$ and a substantially constant baseline phase $\phi_{\{\omega\}}$ at frequency $\{\omega\}$. At frequency $\{\omega\}$ parasitic signal component 54 has a phase shift from the baseline of $\phi_{\{\omega\}}'$ and an amplitude $A'_{\{\omega\}}$. Unless indicated otherwise, the following explanation considers one specific frequency, herein termed ω , although it will be appreciated that the explanation applies to all frequencies generated in coil 27.

50 [0049] The total combined signal M_{ω} received from sensor coil 27, including both position and parasitic signal components may generally be expressed as:

$$\bar{M}_{\omega} = \bar{A}_{\omega} + \bar{A}'_{\omega} \quad (2a)$$

55

so that the amplitude $|M_{\omega}|$ is given by

$$|\bar{M}_\omega| = |\bar{A}_\omega + \bar{A}'_\omega| \quad (2b)$$

5 wherein \bar{A}_ω and \bar{A}'_ω are the phasors of the position signal component and the parasitic signal component respectively, at frequency ω .

[0050] It will be observed in equation (2b) and from Fig. 3 that for each of the signal frequency components $|\bar{M}_\omega|$, the superposition of the parasitic signal component will cause a phase shift in the total detected signal, relative to the signal phase in the absence of metal tool 40, given by:

10

$$\phi_\omega^{\text{total}} = \arctan \left[\frac{A_\omega \sin \phi_\omega + A'_\omega \sin \phi'_\omega}{A_\omega \cos \phi_\omega + A'_\omega \cos \phi'_\omega} \right] \quad (3)$$

15

[0051] In preferred embodiments of the present invention, signal processing circuitry 34 and computer 36 detect and record baseline phases ϕ_ω for all different frequencies received from sensor coils 27, 28 and 29, or for other systems described hereinabove such as the single axis system, in the absence of any metal or other interfering magnetic field-responsive objects in the vicinity of probe 20. Alternatively, undisturbed phases of the position signal components may have been determined in advance for system 10 or are known based on the operation of the system. When metal tool 40 is introduced into the vicinity of probe 20, the phase shift due to the parasitic components engendered thereby in the signals is measured at each separate frequency.

[0052] Fig. 4 is a schematic flow chart showing a method for choosing frequencies to track probe 20, according to a preferred embodiment of the present invention. For simplicity, the following description refers only to radiator coil 22 and sensor coil 27, but it will be understood that the method shown in Fig. 4 applies to any combination of a radiator coil and a sensor coil in system 10. In an initialization phase a baseline phase value ϕ_ω is measured by circuitry 34 from the voltages and currents induced in coil 27. The baseline phase value ϕ_ω is measured at each of the frequencies of $\{\omega_i\}$ and each value is recorded in computer 36. During an operation phase the value of $\phi_\omega^{\text{total}}$ and the absolute value of the difference, $|\phi_\omega^{\text{total}} - \phi_\omega|$, is measured and recorded for each frequency of $\{\omega_i\}$. In the event that the absolute difference is not equal to zero, indicating that a parasitic signal component due to tool 40 is present, computer 36 selects the frequency having the smallest absolute difference. This frequency is used when evaluating $|\bar{M}_\omega|$ in equation (2b). It will be appreciated that applying the method described hereinabove to all combinations of radiator coils and sensor coils in system 10 enables a complete determination of the position and orientation of probe 20.

[0053] As stated hereinabove, equations (2a) and (2b) apply for frequency ω applied to sensor coil 27. As the frequency ω is varied, values of A_ω , ϕ_ω , A'_ω and ϕ'_ω vary. As is known in the art, values of A_ω and A'_ω are directly proportional to the current at which the specific radiator coil, assumed herein to be radiator coil 22, generating the field is being driven and which sensor coil 27 is detecting. Thus $A_\omega = \beta A_0$, and $A'_\omega = \beta A'_0$ where β is a constant, ω_0 is an arbitrary frequency in $\{\omega_i\}$, and A_0 and A'_0 are the amplitudes of the position and parasitic signal components at frequency ω_0 .

40 Also, for small variations of frequency ω , ϕ'_ω is linearly dependent on frequency ω , so that

$$\phi'_\omega \equiv \phi'_0 + \gamma \Delta \omega \quad (4)$$

45

where $\Delta \omega = \omega - \omega_0$,

γ is a constant, corresponding to a value of the derivative $\frac{\Delta \phi}{\Delta \omega}$,
 ϕ'_ω is the parasitic phase and
 ϕ'_0 is the position phase.

50

At a particular frequency ω_i , equation (2a) can be rewritten as:

$$\bar{M}_i = \bar{A}_i + \bar{A}'_i \quad (5a)$$

55

where \bar{M}_i is a phasor representing the measured field at ω_i ,
 \bar{A}_i is a phasor representing the unperturbed field, and
 \bar{A}'_i is a phasor representing the perturbing field due to tool 40. Equation (5a) can be rewritten as follows:

$$\bar{M}_i = \bar{A}_i + a_i' e^{i\phi_i} \quad (5b)$$

5 where a_i' and ϕ_i' are the perturbing amplitude and phase at ω_i .
 Equation (5b) can also be rewritten:

$$\bar{M}_i = \beta_i |A_0| e^{i\phi_i} + \beta_i a_0' e^{i(\phi_0' + \gamma(\omega_i - \omega_0))} \quad (5c)$$

10 where a_0' and ϕ_0' are the perturbing amplitude and phase, and A_0 is the unperturbed amplitude, at ω_0 ,
 ϕ_i is the unperturbed phase shift at ω_i ,

15

$$\beta_i = \left| \frac{\bar{M}_i}{\bar{M}_0} \right|, \quad$$

20 and $\gamma = \frac{\partial \phi}{\partial \omega}$.

[0054] In equation (5c) A_0 , a_0' , and ϕ_0' are unknown, and ϕ_i , β_i , γ , ω_0 , and ω_i are known, or in the case of γ may be found from one other frequency apart from ω_0 and ω_i by using the graph of Fig. 1 relating permeability to frequency. Alternatively, γ may be assumed to be unknown. Thus, if \bar{M}_i is measured at four known separate frequencies, equation (5c) can be solved for A_0 , the position signal component. Most preferably, frequencies $\{\omega_1\}$, $\{\omega_2\}$ and $\{\omega_3\}$ in system 25 10 comprise more than four separate frequencies, so that a plurality of values of A_0 can be determined, and a final value of A_0 calculated by one of the processes of averaging known in the art. Alternatively or additionally, when frequencies $\{\omega_1\}$, $\{\omega_2\}$ and $\{\omega_3\}$ in system 10 comprise more than four separate frequencies, equation (5c) may be adapted to comprise other parameters describing at least some A_0 , a_0' , and ϕ_0' . For example, values of A_0 and a_0' can be assumed to depend on frequency ω in a linear or a nonlinear manner, and appropriate constants can be included in equation (5c), as is known in the art.

[0055] It will thus be appreciated that by varying the excitation frequency of each radiator coil, and measuring the total signal generated in each sensor coil at these frequencies, the position component of the signal can be determined regardless of the presence of parasitic components. It will also be appreciated that varying the excitation frequency of each radiator coil by a plurality of frequencies, wherein the plurality is fewer than four, will give useful information 35 regarding factors associated with tracking objects in the presence of interfering articles.

[0056] It will further be appreciated that the preferred embodiments described above are cited by way of example, and that the present invention is not limited to what has been particularly shown and described hereinabove. Rather, the scope of the present invention includes both combinations and subcombinations of the various features described hereinabove, as well as variations and modifications thereof which would occur to persons skilled in the art upon reading 40 the foregoing description and which are not disclosed in the prior art.

Claims

45 1. A method for tracking an object, comprising:

producing an unperturbed energy field at a plurality of predetermined frequencies in the vicinity of the object; determining a characteristic of a perturbing energy field induced responsive to the unperturbed field, due to introduction of an article responsive to the unperturbed field into the vicinity of the object; 50 receiving a plurality of resultant signals responsive to the unperturbed and perturbing energy fields generated at a location of the object after introduction of the article; determining an optimal frequency for the unperturbed energy field from amongst the plurality of predetermined frequencies responsive to a parameter of the resultant signals; and determining spatial coordinates of the object responsive to the resultant signal at the optimal frequency.

55 2. A method according to claim 1, wherein producing the unperturbed energy field at the plurality of predetermined frequencies comprises scanning the frequencies sequentially.

3. A method according to claim 1, wherein producing the unperturbed energy field at the plurality of predetermined frequencies comprises multiplexing at least some of the frequencies.

4. A method according to claim 1, wherein receiving the plurality of resultant signals comprises:

5 measuring a baseline phase value ϕ_ω of each of the plurality of resultant signals at the respective plurality of predetermined frequencies before introduction of the article; and
 measuring a phase shift $\phi_\omega^{\text{total}}$ at the respective plurality of predetermined frequencies after introduction of the article, so that the parameter comprises a term $|\phi_\omega^{\text{total}} - \phi_\omega|$ for each of the plurality of predetermined frequencies; and

10 15 wherein determining the optimal frequency comprises determining a frequency ω at which $|\phi_\omega^{\text{total}} - \phi_\omega|$ is a minimum.

15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100 105 110 115 120 125 130 135 140 145 150 155 160 165 170 175 180 185 190 195 200 205 210 215 220 225 230 235 240 245 250 255 260 265 270 275 280 285 290 295 300 305 310 315 320 325 330 335 340 345 350 355 360 365 370 375 380 385 390 395 400 405 410 415 420 425 430 435 440 445 450 455 460 465 470 475 480 485 490 495 500 505 510 515 520 525 530 535 540 545 550 555 560 565 570 575 580 585 590 595 600 605 610 615 620 625 630 635 640 645 650 655 660 665 670 675 680 685 690 695 700 705 710 715 720 725 730 735 740 745 750 755 760 765 770 775 780 785 790 795 800 805 810 815 820 825 830 835 840 845 850 855 860 865 870 875 880 885 890 895 900 905 910 915 920 925 930 935 940 945 950 955 960 965 970 975 980 985 990 995 1000 1005 1010 1015 1020 1025 1030 1035 1040 1045 1050 1055 1060 1065 1070 1075 1080 1085 1090 1095 1100 1105 1110 1115 1120 1125 1130 1135 1140 1145 1150 1155 1160 1165 1170 1175 1180 1185 1190 1195 1200 1205 1210 1215 1220 1225 1230 1235 1240 1245 1250 1255 1260 1265 1270 1275 1280 1285 1290 1295 1300 1305 1310 1315 1320 1325 1330 1335 1340 1345 1350 1355 1360 1365 1370 1375 1380 1385 1390 1395 1400 1405 1410 1415 1420 1425 1430 1435 1440 1445 1450 1455 1460 1465 1470 1475 1480 1485 1490 1495 1500 1505 1510 1515 1520 1525 1530 1535 1540 1545 1550 1555 1560 1565 1570 1575 1580 1585 1590 1595 1600 1605 1610 1615 1620 1625 1630 1635 1640 1645 1650 1655 1660 1665 1670 1675 1680 1685 1690 1695 1700 1705 1710 1715 1720 1725 1730 1735 1740 1745 1750 1755 1760 1765 1770 1775 1780 1785 1790 1795 1800 1805 1810 1815 1820 1825 1830 1835 1840 1845 1850 1855 1860 1865 1870 1875 1880 1885 1890 1895 1900 1905 1910 1915 1920 1925 1930 1935 1940 1945 1950 1955 1960 1965 1970 1975 1980 1985 1990 1995 2000 2005 2010 2015 2020 2025 2030 2035 2040 2045 2050 2055 2060 2065 2070 2075 2080 2085 2090 2095 2100 2105 2110 2115 2120 2125 2130 2135 2140 2145 2150 2155 2160 2165 2170 2175 2180 2185 2190 2195 2200 2205 2210 2215 2220 2225 2230 2235 2240 2245 2250 2255 2260 2265 2270 2275 2280 2285 2290 2295 2300 2305 2310 2315 2320 2325 2330 2335 2340 2345 2350 2355 2360 2365 2370 2375 2380 2385 2390 2395 2400 2405 2410 2415 2420 2425 2430 2435 2440 2445 2450 2455 2460 2465 2470 2475 2480 2485 2490 2495 2500 2505 2510 2515 2520 2525 2530 2535 2540 2545 2550 2555 2560 2565 2570 2575 2580 2585 2590 2595 2600 2605 2610 2615 2620 2625 2630 2635 2640 2645 2650 2655 2660 2665 2670 2675 2680 2685 2690 2695 2700 2705 2710 2715 2720 2725 2730 2735 2740 2745 2750 2755 2760 2765 2770 2775 2780 2785 2790 2795 2800 2805 2810 2815 2820 2825 2830 2835 2840 2845 2850 2855 2860 2865 2870 2875 2880 2885 2890 2895 2900 2905 2910 2915 2920 2925 2930 2935 2940 2945 2950 2955 2960 2965 2970 2975 2980 2985 2990 2995 3000 3005 3010 3015 3020 3025 3030 3035 3040 3045 3050 3055 3060 3065 3070 3075 3080 3085 3090 3095 3100 3105 3110 3115 3120 3125 3130 3135 3140 3145 3150 3155 3160 3165 3170 3175 3180 3185 3190 3195 3200 3205 3210 3215 3220 3225 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5230 5235 5240 5245 5250 5255 5260 5265 5270 5275 5280 5285 5290 5295 5300 5305 5310 5315 5320 5325 5330 5335 5340 5345 5350 5355 5360 5365 5370 5375 5380 5385 5390 5395 5400 5405 5410 5415 5420 5425 5430 5435 5440 5445 5450 5455 5460 5465 5470 5475 5480 5485 5490 5495 5500 5505 5510 5515 5520 5525 5530 5535 5540 5545 5550 5555 5560 5565 5570 5575 5580 5585 5590 5595 5600 5605 5610 5615 5620 5625 5630 5635 5640 5645 5650 5655 5660 5665 5670 5675 5680 5685 5690 5695 5700 5705 5710 5715 5720 5725 5730 5735 5740 5745 5750 5755 5760 5765 5770 5775 5780 5785 5790 5795 5800 5805 5810 5815 5820 5825 5830 5835 5840 5845 5850 5855 5860 5865 5870 5875 5880 5885 5890 5895 5900 5905 5910 5915 5920 5925 5930 5935 5940 5945 5950 5955 5960 5965 5970 5975 5980 5985 5990 5995 6000 6005 6010 6015 6020 6025 6030 6035 6040 6045 6050 6055 6060 6065 6070 6075 6080 6085 6090 6095 6100 6105 6110 6115 6120 6125 6130 6135 6140 6145 6150 6155 6160 6165 6170 6175 6180 6185 6190 6195 6200 6205 6210 6215 6220 6225 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7230 7235 7240 7245 7250 7255 7260 7265 7270 7275 7280 7285 7290 7295 7300 7305 7310 7315 7320 7325 7330 7335 7340 7345 7350 7355 7360 7365 7370 7375 7380 7385 7390 7395 7400 7405 7410 7415 7420 7425 7430 7435 7440 7445 7450 7455 7460 7465 7470 7475 7480 7485 7490 7495 7500 7505 7510 7515 7520 7525 7530 7535 7540 7545 7550 7555 7560 7565 7570 7575 7580 7585 7590 7595 7600 7605 7610 7615 7620 7625 7630 7635 7640 7645 7650 7655 7660 7665 7670 7675 7680 7685 7690 7695 7700 7705 7710 7715 7720 7725 7730 7735 7740 7745 7750 7755 7760 7765 7770 7775 7780 7785 7790 7795 7800 7805 7810 7815 7820 7825 7830 7835 7840 7845 7850 7855 7860 7865 7870 7875 7880 7885 7890 7895 7900 7905 7910 7915 7920 7925 7930 7935 7940 7945 7950 7955 7960 7965 7970 7975 7980 7985 7990 7995 8000 8005 8010 8015 8020 8025 8030 8035 8040 8045 8050 8055 8060 8065 8070 8075 8080 8085 8090 8095 8100 8105 8110 8115 8120 8125 8130 8135 8140 8145 8150 8155 8160 8165 8170 8175 8180 8185 8190 8195 8200 8205 8210 8215 8220 8225 8230 8235 8240 8245 8250 8255 8260 8265 8270 8275 8280 8285 8290 8295 8300 8305 8310 8315 8320 8325 8330 8335 8340 8345 8350 8355 8360 8365 8370 8375 8380 8385 8390 8395 8400 8405 8410 8415 8420 8425 8430 8435 8440 8445 8450 8455 8460 8465 8470 8475 8480 8485 8490 8495 8500 8505 8510 8515 8520 8525 8530 8535 8540 8545 8550 8555 8560 8565 8570 8575 8580 8585 8590 8595 8600 8605 8610 8615 8620 8625 8630 8635 8640 8645 8650 8655 8660 8665 8670 8675 8680 8685 8690 8695 8700 8705 8710 8715 8720 8725 8730 8735 8740 8745 8750 8755 8760 8765 8770 8775 8780 8785 8790 8795 8800 8805 8810 8815 8820 8825 8830 8835 8840 8845 8850 8855 8860 8865 8870 8875 8880 8885 8890 8895 8900 8905 8910 8915 8920 8925 8930 8935 8940 8945 8950 8955 8960 8965 8970 8975 8980 8985 8990 8995 9000 9005 9010 9015 9020 9025 9030 9035 9040 9045 9050 9055 9060 9065 9070 9075 9080 9085 9090 9095 9100 9105 9110 9115 9120 9125 9130 9135 9140 9145 9150 9155 9160 9165 9170 9175 9180 9185 9190 9195 9200 9205 9210 9215 9220 9225 9230 9235 9240 9245 9250 9255 9260 9265 9270 9275 9280 9285 9290 9295 9300 9305 9310 9315 9320 9325 9330 9335 9340 9345 9350 9355 9360 9365 9370 9375 9380 9385 9390 9395 9400 9405 9410 9415 9420 9425 9430 9435 9440 9445 9450 9455 9460 9465 9470 9475 9480 9485 9490 9495 9500 9505 9510 9515 9520 9525 9530 9535 9540 9545 9550 9555 9560 9565 9570 9575 9580 9585 9590 9595 9600 9605 9610 9615 9620 9625 9630 9635 9640 9645 9650 9655 9660 9665 9670 9675 9680 9685 9690 9695 9700 9705 9710 9715 9720 9725 9730 9735 9740 9745 9750 9755 9760 9765 9770 9775 9780 9785 9790 9795 9800 9805 9810 9815 9820 9825 9830 9835 9840 9845 9850 9855 9860 9865 9870 9875 9880 9885 9890 9895 9900 9905 9910 9915 9920 9925 9930 9935 9940 9945 9950 9955 9960 9965 9970 9975 9980 9985 9990 9995 9999

at least four numbers respectively corresponding to the at least four frequencies, so as to generate at least four equations; and
 solving the at least four equations for the position signal amplitude A_0 .

5 13. Object tracking apparatus, comprising:

a radiator, which generates an energy field at a plurality of predetermined frequencies in the vicinity of the object;
 10 a sensor, fixed to the object, which generates a plurality of signals responsive to the energy field and to an interfering article responsive to the energy field; and
 signal processing circuitry, which receives the plurality of signals from the sensor and determines an optimal frequency for the energy field from amongst the plurality of predetermined frequencies responsive to a parameter of the signals, and which determines position coordinates of the object responsive to the signal at the optimal frequency.

15 14. Apparatus according to claim 13, wherein the radiator generates the energy field at the plurality of predetermined frequencies by scanning the frequencies sequentially.

20 15. Apparatus according to claim 13, wherein the radiator generates the energy field at the plurality of predetermined frequencies by multiplexing at least some of the frequencies.

16. Apparatus according to claim 13, wherein the parameter comprises a phase shift, and wherein the optimal frequency comprises the frequency where the phase shift is a minimum.

25 17. Apparatus according to claim 16, wherein the signal processing circuitry determines the position coordinates of the object responsive to an amplitude of one of the plurality of signals at the frequency where the phase shift is a minimum.

18. Apparatus according to claim 13, wherein the energy field comprises a magnetic field.

30 19. Apparatus according to claim 18, wherein the plurality of signals comprise a plurality of electrical signals which are generated responsive to the magnetic field.

20. Object tracking apparatus, comprising:

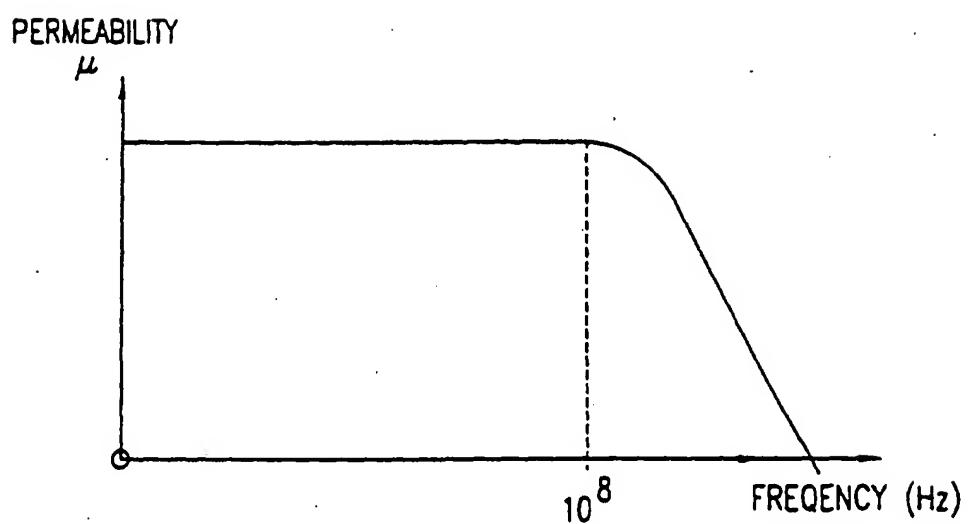
35 a radiator, which generates an energy field comprising a plurality of predetermined frequencies in the vicinity of the object;
 a sensor, fixed to the object, which generates a respective plurality of signals responsive to the energy field and to an interfering article responsive to the energy field; and
 40 signal processing circuitry, which receives the plurality of signals from the sensor and determines one or more factors conditional on spatial coordinates of the object responsive to the signals and their corresponding frequencies.

45 21. Apparatus according to claim 20, wherein the plurality of frequencies comprises at least four frequencies, and wherein the one or more factors comprise the spatial coordinates of the object.

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FIG. 1
(PRIOR ART)



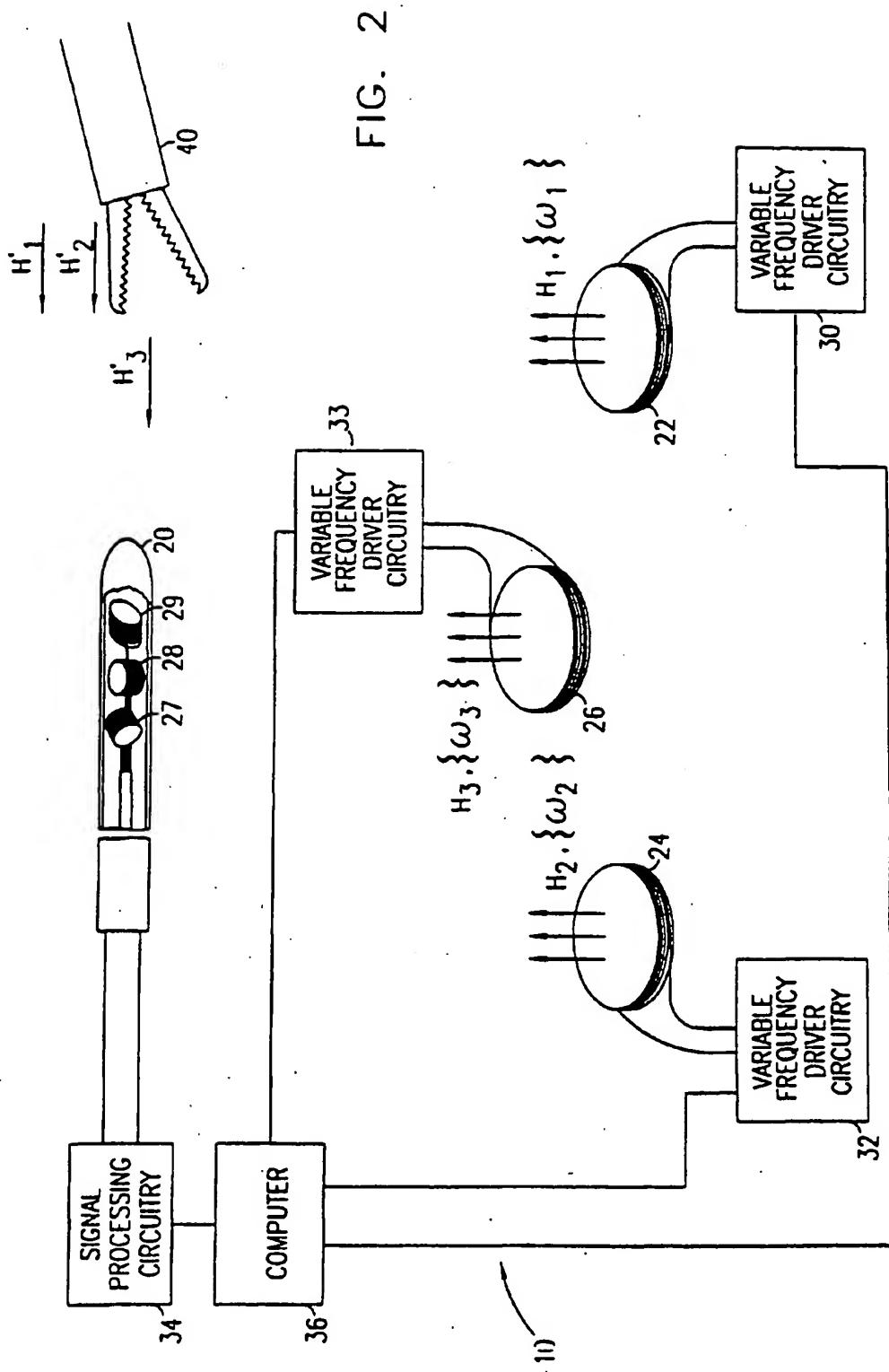


FIG. 3

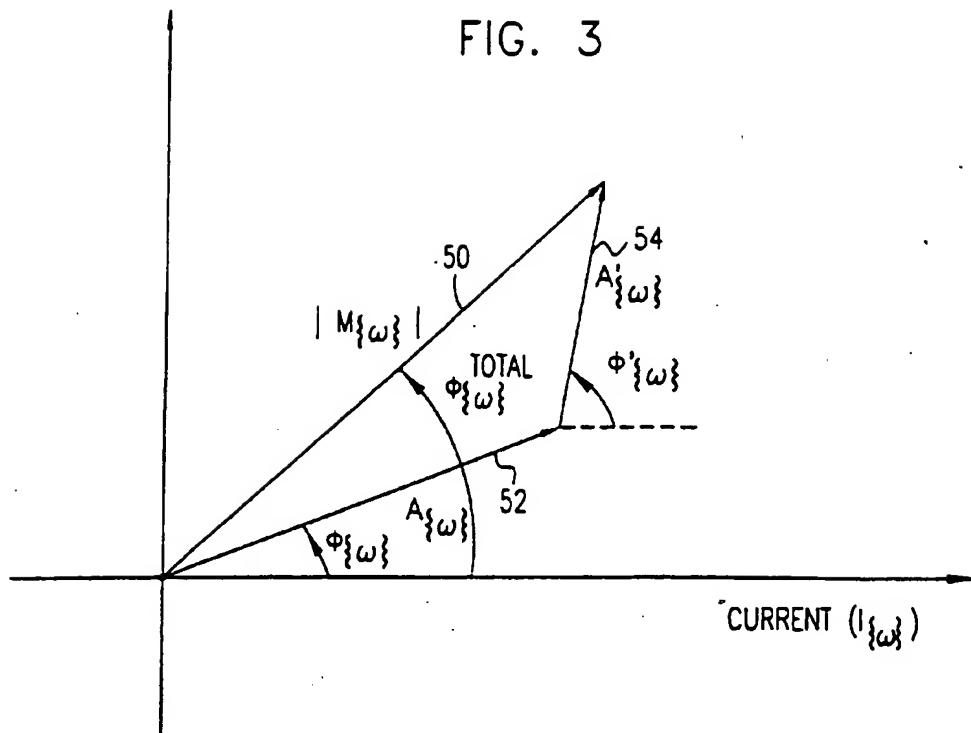


FIG. 4

